Diaphragm valve hydraulic behavior depending on operating pressure

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Abstract

In this study, a hydraulically operated and diaphragm-actuated type of diaphragm valve using an elastic diaphragm was tested. With this type of valve, the opening fraction depends on the pipeline pressure; thus, it is important to determine the minimum operating pressure. The outlet pressure was revealed as the critical pressure ensuring the full opening. The valve flow coefficient was found to be a good indicator of the valve opening fraction. A test procedure was presented to determine the minimum outlet pressure. The pressure had to be continuously increased during testing to avoid hysteresis. An unsteady valve behavior was observed after a sudden intense pressure drop.

Introduction

Diaphragm valves are often used for turning on and off the flow to field irrigation stations. These valves can have pressure sustaining and reducing functions with an appropriate pilot, but in this work, these functions are not studied. The type of diaphragm valve tested in this study (Fig. 1) is diaphragm-actuated and hydraulically operated. The diaphragm of this type of valve is an elastomer, which is hydraulically actuated and operates as an obturator. This simplifies a valve design because the diaphragm performs two functions: actuation and closing. The closing function generates a certain amount of stress on the diaphragm, whereas in other valves, the closing function is performed by a dedicated part (for example, a rigid disk).

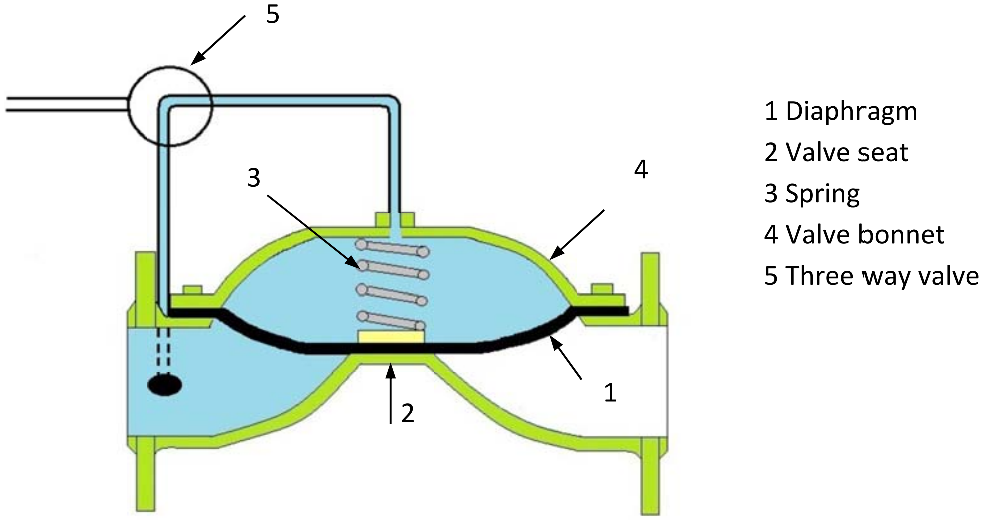

Fig. 1. Schematic of diaphragm valve.

The above-mentioned valve has a seat on which the diaphragm closes the flow, and a spring is located between the diaphragm and valve bonnet. The space between the diaphragm and valve bonnet forms a chamber. If the valve is open, and the three-way valve is connecting the chamber to the upstream pressure then the chamber is pressurized, and a balance is attained between the upper and lower diaphragm forces because the upper and lower pressure and area are the same. The spring is required to start the closing phase. Once the diaphragm begins to close, a decrease in the outlet pressure occurs, creating an imbalance that causes the diaphragm to close.

To open the valve, the chamber needs to be depressurized by turning the three-way valve to connect the chamber and atmosphere. A full opening is not immediately achieved, owing to there is a balance between the upper diaphragm forces (spring and diaphragm stiffness) and lower diaphragm forces (pressure and momentum), and thus, the valve cross-sectional area at the valve seat changes depending on the pipe pressure. This study is focused to choose a good indicator of the valve opening and determine the main variable controlling the opening.

Some manufacturers provide the value of the required minimum pressure for a full opening; however, there are no standard procedures for determining this pressure. For instance, ISO

9644 (2008), which specifies a test method for determining the pressure losses in irrigation valves, states the following: "Conduct these tests at a pressure of approximately two-thirds of the nominal pressure (as specified by the manufacturer) of the valve." The maximum operating pressure head for irrigation cast iron valves is 160 m, which implies that the test pressure head should be approximately 100 m, which is very high for irrigation sets. It needs to be determined what would be the result if the operating pressure head is lower than 100 m. In this case the effect on the relationship between the head loss and discharge has to be identified.

This paper presents the experience acquired through many years of performing valve tests at the Hydraulic Laboratory of Lleida University. Moreover, this paper discusses the hydraulic behavior of the selected diaphragm valve, highlights the importance of the outlet pressure for appropriate operation, and describes a protocol for testing diaphragm valves to determine the minimum operating pressure required to achieve a full valve opening.

Material and methods

One specimen each for both 3-and 5-inch metal-flanged diaphragm valves (from RIS Iberia manufacturer) was tested at the Hydraulic Laboratory at Lleida University. The test bench (Fig. 2) consists of an 18 kW centrifugal pump and an electromagnetic flow meter (125 mm diameter) with a maximum discharge of 200 m^3/h and an accuracy of 0.5%. The valve was inserted in a straight section in accordance with the ISO 9644 (2008) recommended distances. A differential pressure gauge (100 m full scale with 0.1% accuracy) was used to measure the bench head loss (ΔH_b), including the valve head loss (ΔH_v) and piping head loss (ΔH_p). Another gauge was used to measure the valve outlet pressure head with the same characteristics as above.

$$\Delta H_b = \Delta H_v + \Delta H_p \qquad (1)$$

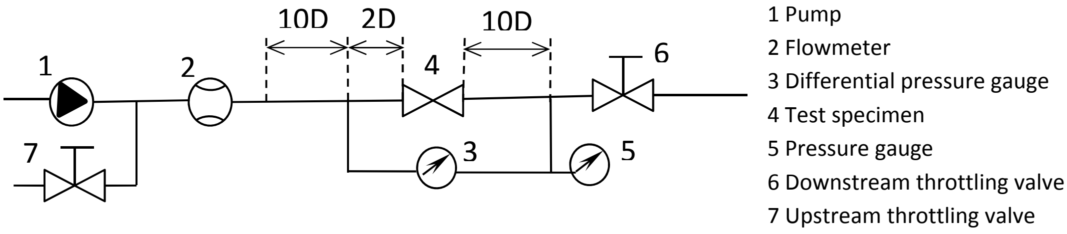

Fig. 2. Schematic of test bench (D: pipe diameter).

A PVC pipe was used, and the pipe head loss was calculated using the Veronese–Datei equation (Carrión, Tarjuelo, and Hernández, 2013):

$$\Delta H_p(\mathrm{m}) = 0.00092\, L\, \frac{Q^{1.8}}{D^{4.8}} \qquad (2)$$

Here, L is the length (m), Q is the discharge (m^3/s), and D is the diameter (m).

The throttling valves used (items 6 and 7 in Fig. 2) were 140-mm-diameter gate valves.

Knowing ΔH_b and ΔH_p, the valve head loss can be calculated from Eq. (1).

The inlet valve pressure head (H_i) was calculated as

$$H_i = H_o + \Delta H_b \qquad (3)$$

where H_o is the outlet pressure head and H_i is the inlet pressure head.

The following two flow coefficients can be used to characterize the valve head loss:

1. Valve head loss coefficient, C, which is used to determine the head loss related to the discharge:

$$C\ (\mathrm{m}^{-5}\cdot \mathrm{s}^2) = \frac{\Delta H_v}{Q^2} \qquad (4)$$

2. Valve flow coefficient, K_v, which is used to determine the flow rate required to create a unit head loss across a valve (Tullis, 1989):

$$K_v(\mathrm{m}^{2.5}\cdot \mathrm{s}^{-1}) = \frac{Q}{\sqrt{\Delta H_v}} \qquad (5)$$

This coefficient is often used to compare the flow capacities between valves.

Initially, the throttling valves of the test bench were open; thus, the pump discharge was maximum, achieving a low pressure and discharge at the valve. The upstream throttling valve was gradually closed, and the inlet pressure and discharge across the valve were, therefore, increased until a nominal discharge was achieved. The discharge and pressure were recorded for each step. The nominal discharge was a value recommended by the valve manufacturer; otherwise, nominal discharge occurred when an inlet flow velocity between 2–3 m/s was achieved. At this instant, the downstream throttling valve was gradually closed, leading to the highest valve outlet pressure and lowest discharge.

Results

Fig. 3 shows the inlet and outlet pressure head evolution during a typical test. The vertical distance between a point and the bisector line represents the valve head loss. It can be observed that at the beginning of the test, the outlet pressure head is very low compared with the inlet pressure head. This is owing to the fact that the water pressure is insufficient to compress the spring, and thus, the valve is nearly closed. This pressure difference causes an asymmetrical deformation of the diaphragm. The upstream throttling valve was gradually closed until an inlet pressure head of 15.6 m was achieved. The downstream throttling valve was then gradually closed.

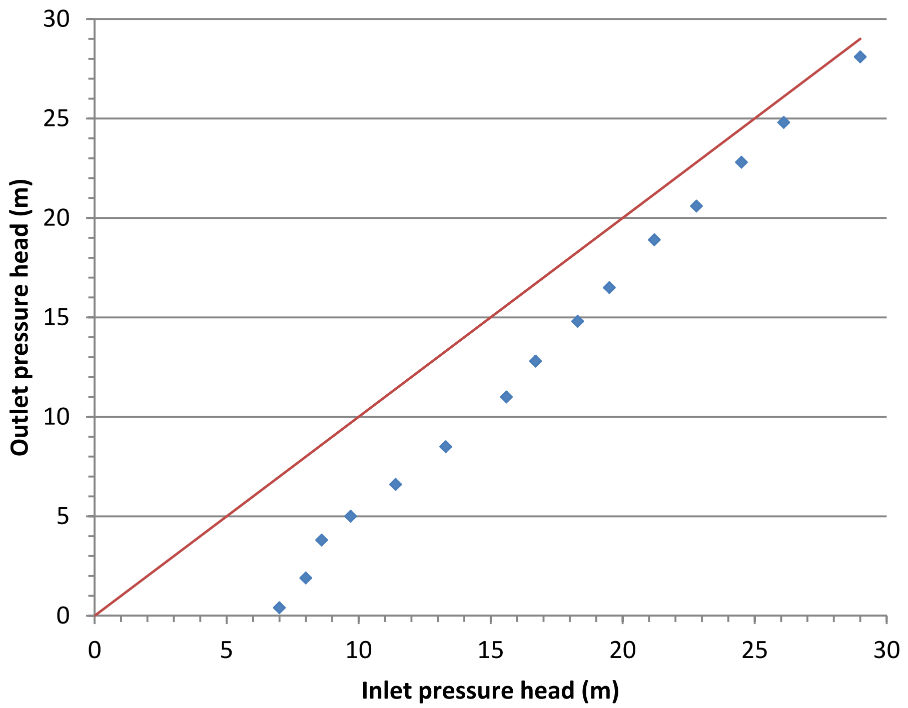

Fig. 3. Inlet and outlet pressure head evolution during test on 3-inch valve.

It should be noted that the vertical distance between a point and the bisector line in Fig. 3 corresponds to the bench head loss. The head loss is related to the valve opening fraction and discharge through the valve. Thus, the opening fraction of the valve can be inferred by analyzing the bench head loss. The coefficients cited above can be used to analyze the valve head loss. The valve flow coefficient (K_v) was chosen because it has a stronger physical meaning, yielding the discharge per unit head loss.

Another indicative test result showing the relevance of the valve outlet pressure is presented in Table 1. It shows that for the same discharge, different bench head losses could can be obtained depending on the valve pressure head. For high pressure heads, the bench head loss is minimum; this is owing to the valve fully opening.

Inlet pressure head (m)	Outlet pressure head (m)	Discharge (m^3/h)	Bench head loss (m)
8.9	0.6	38	8.3
30.9	28.8	38	2.1

Table 1. Variation of bench head loss depending on outlet pressure head.

Fig. 4 shows the variation in K_v with respect to the outlet pressure head, H_o. It can be observed that low K_v values are achieved for low H_o values, showing that the valve is not fully open. As H_o increases, so does K_v up to the H_o value at which K_v remains constant. This is because the valve is fully opened. This behavior is observed during all the conducted tests. The outlet pressure at which K_v stabilizes can be called the Minimum Outlet Pressure (*MOP)*, which should be attained to reach the optimum valve performance, i.e., the maximum capacity per unit head loss. For the data shown in Fig. 4, *MOP* is 10.9 m. Thus, the outlet pressure is a relevant variable explaining the opening fraction of the valve. It is recommended to repeat the procedure at least twice to achieve more consistency.

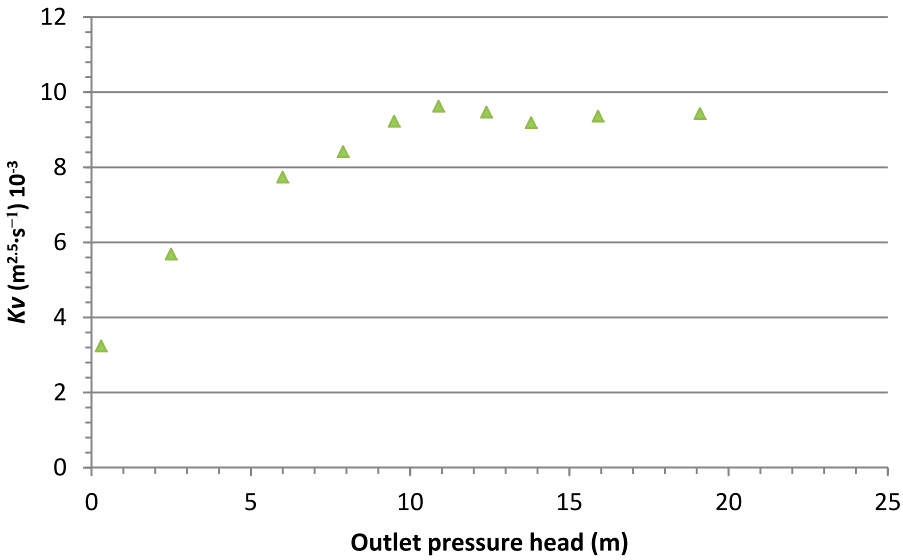

Fig. 4. Variation in K_v with respect to outlet pressure head for 3-inch valve.

The average maximum K_v value is another important parameter for characterizing the diaphragm valves.

Fig. 4 also allows predicting the valve head loss if *MOP* is not attained by simply reading the K_v value in the graph corresponding to the expected outlet pressure head and applying Eq. (5), considering the required discharge.

Hysteresis

Increasing and decreasing pressure tests were conducted to check the occurrence of hysteresis. The results are shown in Fig. 5 It can be observed that at the beginning of the decreasing phase, K_v is slightly larger, but when the pressure head is less than *MOP* (10.2 m), more significant differences occur. We infer that this could be owing to the stiffness of the diaphragm. Based on this result, attention should be paid when determining *MOP*, and the pressure should be continuously increased and on no account decreased. Hysteresis does not imply a problem in field operation because when hysteresis occurs, a higher opening fraction is achieved than in its absence.

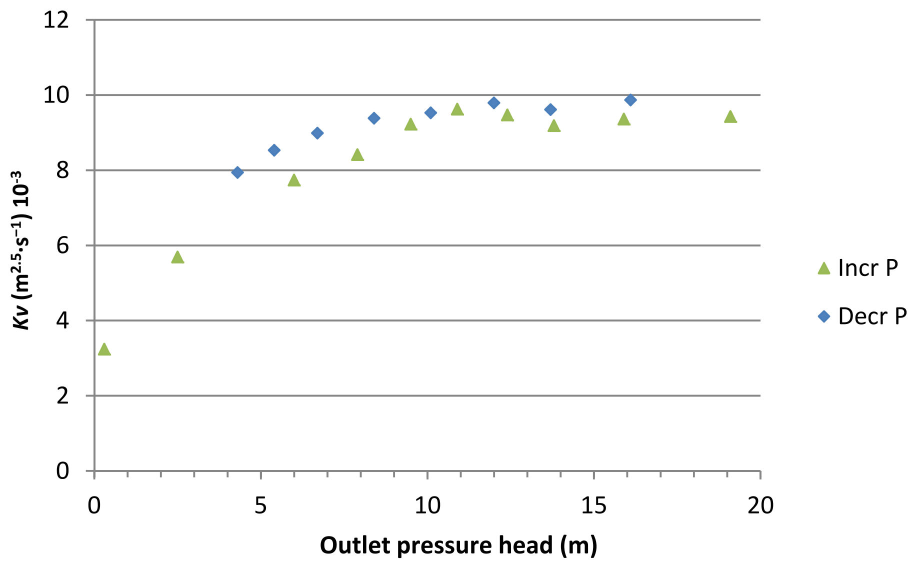

Fig. 5. Variation in K_v with increasing and decreasing outlet pressures for 3-inch valve.

Unsteady valve behavior

Under the bench conditions, when the valve is open and the outlet pressure is substantially decreased, the valve may experience an unsteady behavior of closing and opening without control. This can be explained because when the outlet pressure diminishes beyond a certain value, the valve partially closes and then the discharge diminishes; the pump then increases the pressure, and the valve opens again. Fig.6 shows the oscillation in the outlet pressure head as a function of the initial outlet pressure head. It can be observed that the pressure head at which the selected valve begins to oscillate is 1.9 m. This situation is unlikely to occur, but it was observed during the tests.

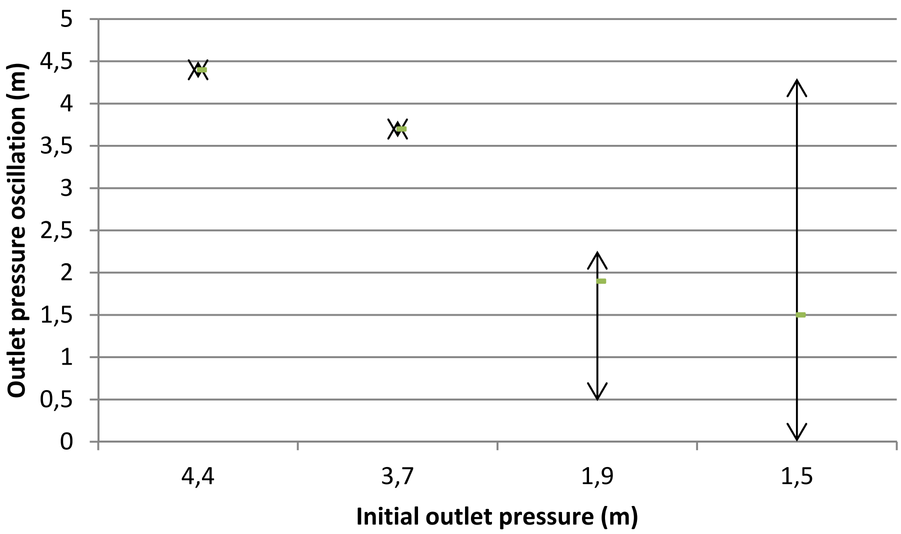

Fig.6. Outlet pressure head oscillation for different initial outlet pressure heads for 5-inch valve.

Conclusion

It was observed that for the same discharge, different bench head losses can be obtained depending on the valve pressure head. This is showing that valve opening fraction is related to pressure. The valve flow coefficient (K_v) was found to be a good indicator of valve opening. A minimum outlet pressure should be reached to ensure full valve opening, so this is an important data that should be provided by manufacturers. However, there is no standard specifying a method to determine this pressure; nevertheless, a protocol was proposed in this paper.

The diaphragm valve showed hysteresis depending if increasing or decreasing pressures are applied during tests. An oscillation behavior of closing and opening was observed when the outlet pressure is below a certain pressure.

Data availability

All data generated during the study are available from the corresponding author by request.

Acknowledgment

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